The "Master Enabler" – In-orbit Servicing

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Some of the most noteworthy missions in space exploration have occurred in the last two decades and owe their success to on-orbit servicing. The tremendously successful Hubble Space Telescope repair and upgrade missions, as well as the completed assembly of the International Space Station (ISS) and its full utilization, lead us to the next chapter and set of challenges. These include fully exploiting the many space systems already launched, assembling large structures *in situ* thereby enabling new scientific discoveries, and providing systems that reliably and cost-effectively support the next steps in space exploration. In-orbit servicing is a tool—a tool that can serve as the "master enabler" to create space architectures that would otherwise be unattainable. This paper will survey how NASA's satellite-servicing technology development efforts are being applied to the planning and execution of two such ambitious missions, specifically asteroid capture and the in-space assembly of a very large 'life-finding' telescope.

NASA has begun the detailed planning for a mission to deep space to rendezvous with, and robotically retrieve either a large section of an asteroid, or fully capture an entire asteroid. Once secure, this near earth object will be brought to a lunar distant retrograde orbit. Subsequently, a manned vehicle will depart earth to dock with the robotic boulder retrieval vehicle. The crew

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members will then harvest samples and return them to Earth for detailed analyses/scientific evaluation. Servicing technologies already in development are being considered to execute essential elements of the robotic boulder capture sequence.

The second mission, which is in early concept phase, aims to collect data to answer one of mankind's most fundamental questions – are we alone. To search for the existence of life on distant planets, NASA must plan for large telescopes in excess of 20 meters in deep space – telescopes that will defy the limits of what can be assembled on the ground and deployed in space. The present state-of-the-art in large space telescope ground assembly and verification will not work for a life-finder telescope. There is no hope of completely testing such a large telescope on the ground. The optomechanical stability requirements are extreme, and there is no vacuum test facility large enough to conduct integrated systems verification testing. The flight configuration will require an immense sunshield or tube surrounding the telescope to protect it from thermal changes and from stray light, and some never-before-flown system to protect the telescope from vibrations in the spacecraft subsystems. Only on-orbit assembly can produce an observatory of this scale and precision. On-orbit assembly provides the tools and capability to fine-tune the telescope systems to ensure proper operations, while at the same time providing the capability to perform repairs and upgrades to extend its operational life.

Both asteroid capture and deep-space telescope assembly will require a robust, integrated architecture of space assets and technologies to enable them. To maximize Agency efficiency, opportunity, and flexibility, these technologies should not only support the scientific objective of discovering exo-life, but also complement and support NASA's long-term objective to land on Mars. From NASA's experience in Hubble servicing and ISS assembly, it is estimated that both the asteroid retrieval and astronomical observatory will require a common set of technologies: advanced rendezvous and proximity operations (RPO), and dexterous robotics (DxR) both autonomous and teleoperated. This paper will describe recent developments that NASA's Satellite Servicing Capabilities Office (SSCO) has made in state-of-the art technologies and techniques in these two areas.

The majority of these enabling technologies were conceived, tested, and iterated at the Goddard Servicing Technology Center (STC), a 'Skunk Works' facility. The STC contains over a dozen six and seven degree-of-freedom industrial and flight robots; a motion-based platform; aftermarket, low-latency, customized controllers; and custom robotic software and algorithms to simulate the kinematics and dynamics of various space robot systems and space objects.

In particular, the paper will examine recent, highly successful experiments in the areas of RPO and DxR that have been conducted by SSCO on the ISS and on the ground. The successful Argon ground test campaign and the upcoming ISS Raven experiment are establishing a core technology suite for RPO and maturing technologies essential for autonomous rendezvous with non-cooperative objects. This technology suite includes cutting-edge sensing and processing hardware as well as advanced pose algorithms, which will be described in depth within this paper. This satellite servicing RPO system has been baselined for the robotic boulder capture vehicle for the Asteroid Redirect Mission currently under consideration by NASA. It also offers unique benefits to large-telescope assembly, as it would provide an autonomous rendezvous and docking capability for manned and unmanned logistics tugs.

In the area of DxR, NASA's satellite servicing experience with the HST repair missions, as well as recent advancements made during in Robotic Refueling Mission on the ISS and the Remote Robotic Oxidizer Transfer Test on the ground, have given the SSCO team an in-orbit, low latency, telerobotic experience base against challenging interfaces (non-cooperative). From this experience and the robotic technology development performed in the STC, it is clear that the technology required for robotic asteroid boulder capture is imminent. These advancements will be described. Furthermore, the technology roadmap necessary for the assembly of a life-finding telescope has become more defined. Those developments will also be described. The information contained within this paper will help inform and aid future mission developers so they can fold these new, state-of-the-art technologies and capabilities into their planning.